Seasonal - Interannual - Decadal Climate Prediction and Predictability Studies at GFDL

W. Stern, A. Rosati, S. Zhang, R. Gudgel and A. Wittenberg

GFDL/NOAA/Climate-Change-Variability-and-Prediction
http://www.gfdl.noaa.gov/climate-change-variability-and-prediction

Bill.Stern@noaa.gov

UTEP 18 Nov 2010
Motivation for S/I/Decadal prediction at GFDL:
Contribute to NOAA long-lead prediction products and IPCC
Produce seasonal -> Interannual (ENSO)-> Decadal predictions of societal relevance (NOAA Climate Service)

GFDL Historical Perspective

Overview of Climate Prediction and GFDL’s Climate System (includes ECDA)

Predictability / Potential Predictability / “Practical” Potential Predictability

Seasonal Prediction / Predictability

Decadal Prediction / Predictability

Improving S/I/Decadal Climate Prediction:
ECDA enhancements
GCM development – reduce model bias, higher resolution

Summary
In 1955 the Weather Bureau created the General Circulation Research Section and appointed Joe Smagorinsky as its Director

* 1955: Collaboration established between Princeton’s Institute for Advanced Study, the Weather Bureau, Air Force, and Navy to generate a computerized model of atmospheric circulation
* 1967: First model estimate of the impact of carbon dioxide on global temperature
* 1982: GFDL experimental NWP model physics transferred to NMC operational model
* 1985: First diagnosis of weakening ocean circulation in a warming world
* 1990: First simulation of Antarctic ozone hole
* 1991: First community global ocean model completed (MOM1)
* 1995: GFDL Hurricane Prediction System made Operational at NWS/NMC
* 2002: First realistic model-based study of the impact of global warming on hurricane intensity
* 2005: Development of CM2.0 and CM2.1 completed, two of the world’s leading climate models used in 2007 IPCC-AR4.
The Climate Prediction Problem

Climate = set of statistics associated with many different states of the atmosphere/ocean (i.e., for an atmospheric/oceanic field - time and/or space and/or ensemble average, also PDF).

2 classes of climate prediction (Lorenz, 1975):
1\textsuperscript{st} kind = Initial value problem (i.e., future states of atmosphere-ocean depend on initial state.)
2\textsuperscript{nd} kind = forced boundary value problem with (How does a prescribed forcing, such as a doubling of CO\textsubscript{2}, affect a future climate state?)

The Climate Predictability Problem

Predictability for climate prediction of the 1\textsuperscript{st} kind is limited due to rapid growth of errors in estimating the initial state (Lorenz, 1969). But predictability limit is extended for averaged fields relative to deterministic weather prediction because slower growing large errors between averaged fields is the limiting factor along with an ocean that varies on time-scales much longer than weather events.

Ensembles provide a way to sample uncertainties/errors in initial states and models.
GFDL Climate Prediction System - Overview

Tier 1
- Ocean Obs
  - ECDA
  - NCEP RA
  - Obs SST
  - CM2 Ensembles
  - Atmos IC

Tier 2
- Predicted SST
  - AM2 Ensembles
  - AMIP
    - Multi-year ensemble

Climate Forecast Products

SST Forecasts
AM2/LM2 (Delworth et al., 2006; GFDL Global Atm. Development Team, 2004):

FV Dynamical core (S.J. Lin 2004) – AM2.1
2.5° lon X 2.0° lat X 24 vertical levels
(high resolution - 0.5° x 0.5° x 32 vertical levels)
top at ~ 30 km
RAS Convection (Moorthi/Suarez)
Simple cumulus momentum transport (Held)
Ramaswamy et al. radiation
Prognostic cloud scheme (Klein)
UKMO PBL (Lock et al. 2000)
Stern-Pierrehumbert Orographic GWD
LM2 Land Model (Milly)

Ocean (Griffies et al., 2005):

MOM4-SIS – Ocean-Ice
1 deg (1/3 near equator) Tri-polar grid, 50 vertical levels
GFDL Climate Prediction Systems / Experiments:

**Tier 1 – Coupled Atmosphere-Ocean GCM (CM2):**

S/I with fully coupled GCM (CM2.1) – 10 member ensemble, 1 year predictions, 1979->2009
I.C. = Jan1 … Dec1

**Decadal with CM2.1** – 10 member ensemble, 10 year predictions, 1979->2018, I.C. = Jan1 (1971->2009 )

“Biased Twin” with CM2 – 12 member ensemble assim/prediction, 1982->2000

**Tier 2 – Atmospheric GCM (AM2):**

**AMIP** runs (observed SST), 10 member ensemble, 1979 ->1999+

**SSTA_mn** hindcasts with CM2.1 SSTA ensemble mn, 10 member ensemble, 1 year predictions, 1979->2005, IC = May1 and Nov1

**SSTA** hindcasts with CM2.1 SSTA ensemble mn, 10 member ensemble, 1 year predictions, 1979->2005, IC = May1 and Nov1

Real-time forecasts as part of the IRI MM ensemble, four 10 member ensembles (3 predicted SSTA + persisted SSTA), 7 month predictions, 2004 Aug ->,
IC = Jan1, Feb1, …, Dec1
Development of coupled data assimilation system

Ensemble Coupled Data Assimilation estimates the *temporally-evolving probability distribution* of climate states under observational data constraint:

- Multi-variate analysis maintains physical balances between state variables such as T-S relationship – primarily geostrophic balance
- Ensemble filter maintains the nonlinearity of climate evolution
- All coupled components adjusted by observed data through instantaneously-exchanged fluxes
- Optimal ensemble initialization of coupled model with minimum initialization shocks

S. Zhang, M. J. Harrison, A. Rosati, and A. Wittenberg
MWR 2007
Prediction and Predictability Metrics

Anomaly Correlation Coefficients:
  - time series (TCC); spatial patterns (ACC)
Root Mean Square Anomaly Error (RMS)

PDF:
  - Ensemble Anomaly Probability Forecasts
  - Ranked Probability Skill Scores (RPSS)

Potential Predictability (perfect model scenario)

Signal to Noise Ratio = S/N (>1)

Signal (S) – Interannual Stnd. Deviation
Noise (N) – Ensemble Stnd. Deviation

Ensemble spread or correlations (>0) within ensemble

“Practical” Pot. Predictability allows for obs/model errors
  (“Biased Twin” experiments)
Potential Predictability for 1991-2000 indicated via S/N ~1 or greater. AMIP (top left), Coupled (top right), Persisted SST (bot left), APCN Tier 2 (bot right)
NA Precip Signal / Noise: AMIP (top left), Coupled (top right), Tier2 - Ens. Member SSTA (bot left), Ens. Mean SSTA;
Temperature changes associated with ENSO affect ocean ecosystems and global weather patterns, with far-reaching consequences for fisheries, agriculture, and natural disasters. Worldwide losses resulting from the 1997-98 El Niño are estimated at $32-$96 billion.
S/I Predictability Estimates

SST TROP PAC TCC Lat mean
Fv_da_12m_AIEFn_da_fcast_jul_ensm IC=July 1982-2000

SST TROP PAC TCC Lat mean
Fv_da_12m_AIEFn_da_fcast_jul_ens1-6 IC=July 1982-2000

PRECIP DJF USA mean
Fv_da_12m_AIEFn_da_fcast_jul_ensm IC=July 1982-2000

PRECIP DJF USA mean
Fv_da_12m_AIEFn_da_fcast_jul_ens1-6 IC=July 1982-2000 IC=July

PRECIP DJF USA mean
CBH_fcast_jul_ensm IC=July 1982-2000
Ensemble Forecast Probability Distributions

Tercile Forecasts - 3 category probability forecasts (above, normal, below), using historical GCM integrations to define range of anomalies.

Calculate Ranked Probability Score (RPS) and then Ranked ProbabilitySkill Score (RPSS) following Wilks 1995 and Goddard et al., 2003, i.e.,

\[
\text{RPS} = \sum (\text{CPF}_m - \text{CPO}_m)^2, \text{ where } m = 1, 3 \text{ and CP = cumulative probability of a category}
\]

\[
\text{RPSS} = 1 - \frac{\text{RPS}_{\text{fcst}}}{\text{RPS}_{\text{ref}}}, \text{ where}
\]

\[\text{ref} = \text{climatology}\]
Coupled Model Cold Drift in Nino 3.4 Region (lat 5S-5N ave) – Jan IC
Multi-Decadal Scale Variability?

Devils Lake, ND

Lake Mead 2010

USGS

August Water Volume in Lake Mead (millions of acre-feet)

Goldenberg, et al., 2001

JASO–mean Sahel precipitation anomalies 1900–2009

Averages over 20–10N, 20W–10E; 1900–2009 climatology
NOAA NCDC Global Historical Climatology Network data
Atlantic Multi-Decadal Oscillation

**AMO --> mean N. Atlantic SSTA**

Correlation ANN AMO Index vs $T_{ref}$
6-10 year forecast 1978-2003

NOAA/AOML
Pentad Precip Anomalies
Key goal: assess whether climate projections for the next several decades can be enhanced when the models are initialized from observed state of the climate system.

- Use ECDA_ver3.0 for initial conditions from “observed state”
  Produce ocean reanalysis 1970-2010

- Use “workhorse” CM2.1 model from IPCC AR4 [2010]- RCP forcing
  Decadal hindcasts from 1970 - 2009 every year starting in JAN
  Decadal predictions starting from 2001 onwards

- Use experimental high resolution model CM2.5 [2011]
  Decadal predictions starting from 2003 onwards

- Use CM3 model [2011, tentative]- indirect effect, atmospheric chemistry
  Decadal predictions starting from 2001 onwards
The non-stationary of ocean observations is a particular challenge for the estimation of decadal variability.
Ability to represent AMOC in models is a function of observing system

- Use of ARGO plus atmospheric temperature and winds performs best in “twin” experiment

Zhang et al, 2010
Complicating factor: Changing radiative forcing alters not only the thermal structure of the ocean, but its circulation as well. This complicates attribution.
Hi-Resolution Model development

- Simulated variability and predictability is likely a function of the model

- Developing improved models (higher resolution, improved physics, reduced bias) is crucial for studies of variability and predictability

- New global coupled models: CM2.4, CM2.5, CM2.6

<table>
<thead>
<tr>
<th></th>
<th>Ocean</th>
<th>Atmos</th>
<th>Computer</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>CM2.1</td>
<td>100 Km</td>
<td>250 Km</td>
<td>GFDL</td>
<td>Running</td>
</tr>
<tr>
<td>CM2.3</td>
<td>100 Km</td>
<td>100 Km</td>
<td>GFDL</td>
<td>Running</td>
</tr>
<tr>
<td>CM2.4</td>
<td>10-25 Km</td>
<td>100 Km</td>
<td>GFDL</td>
<td>Running</td>
</tr>
<tr>
<td>CM2.5</td>
<td>10-25 Km</td>
<td>50 Km</td>
<td>GFDL</td>
<td>Running</td>
</tr>
<tr>
<td>CM2.6</td>
<td>4-10 Km</td>
<td>25 Km</td>
<td>DOE</td>
<td>In development</td>
</tr>
</tbody>
</table>
Double peak in tropical precipitation a persistent problem in global climate models.
Observed rainfall

GFDL CM2.1
2° Atmosphere
1° Ocean

GFDL CM2.3
1° Atmosphere
1° Ocean

Preliminary results suggest resolving processes on finer spatial scales may lead to significant improvements in climate simulation.
GFDL Coupled Model East Pacific Precipitation (150°W-90°W)

Observed rainfall

GFDL CM2.1
2° Atmosphere
1° Ocean

GFDL CM2.3
1° Atmosphere
1° Ocean

GFDL CM2.4
1° Atmosphere
1/4° Ocean

GFDL CM2.5
1/2° Atmosphere
1/4° Ocean

Preliminary results suggest resolving processes on finer spatial scales may lead to significant improvements in climate simulation.
Summary S/I Prediction

- Results of “Biased” Twin experiments show significant “practical” potential predictability at leads of 5 months or more. “Perfect model” scenario extends potential predictability to at least 9 month lead. ENSO is key to extended S/I predictability.

- Coupled model hindcasts show a significant cold drift across the east-sentral tropical Pacific (Nino 3.4) region which adversely affects longer lead prediction skill of $T_{2m}$ and precipitation in the Tropical Pacific.

- Current research efforts to improve S/I prediction include:
  - Coupled assimilation scheme
  - Investigating improvements to convective parameterization and prognostic clouds
  - Higher resolution
Atlantic SST variability has a rich spectrum with suggested climatic impacts. This motivates attempts to understand the relationship of the AMOC to that variability, and to predict AMOC variations.

The use of ideal twin experiments, in concert with coupled assimilation system, allows an assessment of the potential of various observing systems to observe and predict the AMOC.

Model results suggest that the ARGO network is crucial to the most faithful representation of the AMOC in model analysis.

Predictability experiments show use of ARGO network plus atmospheric analysis provides the most skillful AMOC prediction (skill for AMOC is 78% with ARGO versus 60% without). Inclusion of changing radiative forcing tends to increase skill on longer time scale.

These experiments DO NOT take into account model bias, which is a formidable challenge.

GFDL decadal prediction efforts using observed data are ongoing using ensemble coupled assimilation system and GFDL CM2.1 model.
Decadal Prediction – Further Study

- Decadal climate variability:
  - Crucial piece – predictability may come from both
    - forced component
    - internal variability component
  - ... and their interactions.

- Decadal predictions will require:
  - Better characterization and mechanistic understanding (determines level of predictability)
  - Sustained, global observations
  - Advanced assimilation and initialization systems
  - Advanced models (resolution, physics)
  - Estimates of future changes in radiative forcing

- Decadal prediction is a major scientific challenge

- An equally large challenge is evaluating their utility
DJF 2010-11 Forecast
IC = 01Nov2010

http://www.gfdl.noaa.gov/gfdl-real-time-seasonal-forecasts